FIRST RESULTS ON AIRBORNE LASER SCANNING TECHNOLOGY AS A TOOL FOR THE QUANTIFICATION OF GLACIER MASS BALANCE

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ABSTRACT

In this study airborne laser scanning technology is introduced as a tool for glaciological applications. The method is described with its advantages and limitations and applications in glaciology in recent years and their results are mentioned. Data from a laser scanner flight at Hintereisferner are presented. Due to the dense coverage with data points the results demonstrate the potential for building accurate high-quality DEMs for the whole area of a glacier. The possibilities of multitemporal use of laser scanner techniques are discussed. This technology enables to quantify changes of glaciers both in area and volume and, therefore, raises expectations that it may be used as an independent method for glacier mass balance measurements. Future work is outlined.

INTRODUCTION

The work presented here is carried out as a subproject of the EU-financed project OMEGA (Development of an Operational Monitoring system for European Glacial Areas). The main objective of OMEGA is to develop an operational monitoring system for glacier areas in Europe offering accurate and up-to-date information. The tool will be useful for operational mass balance measurements and is also relevant to global change studies. This objective is achieved by (i) evaluating the potential of airborne and satellite remote sensing, (ii) designing a monitoring system which can utilise different types of earth observation data and connect them with meteorological and glaciological data and (iii) constructing a regional glaciological database (Pellikka et al. 2001). One major aspect for the achievement of the objectives is the generation and utilisation of digital elevation models from spaceborne and airborne data. In this context, airborne laser scanning technology provides the link between satellite-based remote sensing techniques and the ground truth of in-situ measurements on the glaciers.

Besides the provision of calibration data for other techniques (e.g. RADAR measurements) the possibilities and limitations of laser scanning as an independent method for mass balance measurements are investigated and evaluated. The test sites are situated in Norway (Svartisen) and Austria (Hintereisferner, Ötztal). The Hintereisferner test site contains Hintereisferner itself and adjacent Kesselwandferner. The site has been chosen as it has been well investigated for more than 100 years, especially regarding mass balance measurements (e.g. Kuhn et al. 1999). Within the time frame of the OMEGA project 10 airborne laser scanner campaigns are planned at Hintereisferner. The results presented here are from the first data acquisition flight in autumn 2001.

METHODS

Laser scanning Technology

During the last decade airborne laser scanning has made decisive technical improvements and has become a standard and well-accepted method for the acquisition of topographic data for many applications. The method is characterised by a far-reaching degree of automation with digital data recording and computer-based data analysis methods. Laser scanning allows data sampling also under meteorological conditions that are too poor for aerial photography e.g. at low sun angles or even at night, as it uses active illumination.

The airborne laser scanning system is an integrated system, consisting of a Global Positioning System (GPS) receiver, an Inertial Navigation System (INS) and a scanning system using laser technology (see *figure 1*). All components are time–synchronized. The method provides a means to measure the distance between the aircraft and the earth´s surface. When the absolute position of the mounted sensor is known, the z-coordinate of a point on the earth´s surface can easily be calculated from the measured distance. The method allows deriving high-quality DEMs with a horizontal accuracy of less than one metre and a vertical accuracy of up to 0,15 m. (Wever 1999). The main application of airborne laser scanning technology is topographic surveying, especially in forested areas. Other applications are forest management, coastal management, power line management, urban planning and natural hazard management.

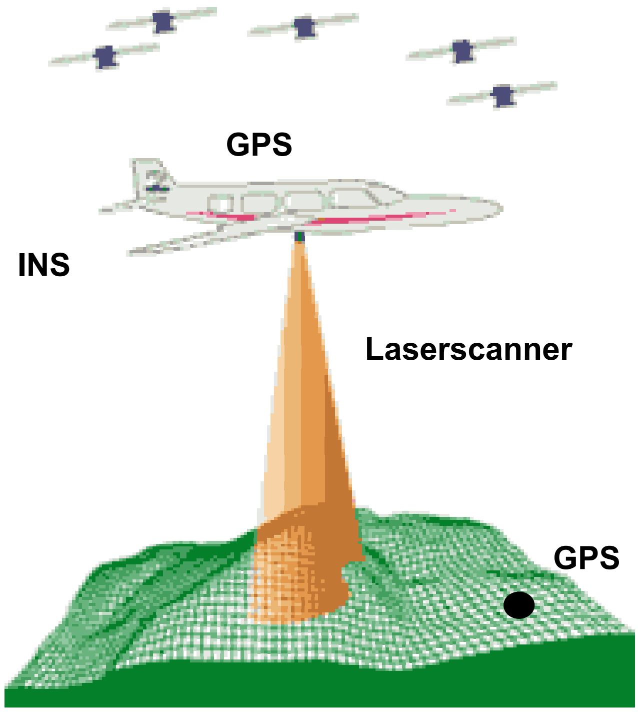

Figure 1: The main components of the airborne laser scanning system (Source: TopScan GmbH, Steinfurt, Germany)

Different technical solutions for the laser scanning system exist. With the laser scanning system used in the project (Airborne Laser Terrain Mapper - ALTM 1225) the laser beam is swept perpendicularly to the ground track, thus producing an even distribution of data points with high accuracy. The density and distribution of the data points depend on the scan angle, the scan frequency, the height above ground, the aircraft speed and the swath overlapping. The absolute position and the attitude of the sensor are calculated from GPS and INS measurements. The flight path of the aircraft is reconstructed with the help of differential GPS. Hence GPS data must be collected at additional reference stations.

The primary results are three-dimensional coordinates of single reflections from which the shape of the earth´s surface can be derived. The key problem in obtaining the data consists in bringing together all necessary elements for georeferencing the laser data, where the quality of each contributing part (GPS, INS, Laser) has to be monitored regarding its accuracy and systematic effects. A comprehensive overview on the synchronisation of laser scanner data and navigation data as well as quality issues is given by Favey (2001). Currently the main technical improvement of laser scanning focuses on assessing and improving the system accuracy by error modelling and by the development of error-correction algorithms. A comprehensive overview of laser scanning technology is given by Ackermann (1999).

Applications in Glaciology

Airborne laser altimetry has only recently been introduced to glaciology. The first experiments with laser profiling (measurement only on a single line below the aircraft) were carried out in Alaska (Echelmeyer et al. 1996; Sapiano et al. 1998; Aðalgeirsdottir et al. 1998) and over the Greenland Ice Sheet (Garvin and Williams 1993). So far, laser scanner measurements in glaciology have been few, although campaigns were undertaken at Hardangerjökulen, Norway (Kennett and Eiken 1997) and Unteraarferner, Switzerland (Favey et al. 1999).

For glacier mass balance studies the calculation of volume changes from a set of digital elevation models (DEMs) from different time periods is an interesting alternative to the time consuming glaciological method (stake measurements) for estimating net mass balance. Airborne laser scanning is opening new possibilities for qualitative and quantitative determination of surface elevation changes of glaciers. The high accuracy and dense coverage (more than 500.000 points per km^2 are feasible) give the possibility of building high-quality DEMs and enable a more reliable measurement of glacier volume change as this is no longer based on only a few single points.

Laser scanning has three main advantages compared to traditional techniques used to define glacier mass balance: (i) It may be used independently of surface texture and external light sources; (ii) it generally gives denser and more accurate measurements under the given conditions and (iii) the establishment and maintaining of ground control points is not needed, with the exception of a GPS reference station in the close vicinity. Therefore, the area of interest for glacier monitoring may be expanded to the entire glacier including the remote firn areas, which are not accessible by photogrammetric means either because of lack of texture or due to the fact that no suitable ground control points can be located. In flat and snow covered parts of a glacier, laser scanning may be able to reach an expected accuracy of 0.2 m in z-direction, as shown over the Greenland Ice Sheet (Garvin and Williams 1993). In such a case, photogrammetry can compete only by increasing the image scale to almost 1:5000. At Unteraarferner it was shown that a determination of the surface elevation change distribution is feasible with an accuracy of 0.5 – 0.7 m as the data acquisition rate and the quality of measurements depends on the slope of the surface and is reduced over crevassed areas (Favey et al. 1999). Kennett and Eiken (1997) found that the accuracy of surface elevations is affected principally by uncertainties in the laser range (ca 7 cm) and the GPS position (ca 10 cm).

DATA

Data Acquisition

Data acquisition is carried out by TopScan GmbH, Steinfurt, Germany (www.topscan.de) using an ALTM 1225 laser scanning system. The major technical parameters of the system are shown in *table 1*. Baltsavias (1999) gives further details and a comparison with other commercial and experimental systems. The ALTM 1225 allows a variable adjustment of scanning angle and measuring frequency. As other modern systems, ALTM 1225 can record the first or last signal of a laser pulse as well as the intensity of the reflected laser signal for each data point. The first airborne laser scanner acquisition flight (out of 10 within the OMEGA project) was carried out on 10 October 2001.

Table 1: Technical Parameters of the ALTM 1225

Measuring frequency	25.000 Hz
Scanning angle	+/- 20°
Scanning frequency	25 Hz
Max. operating altitude above ground	2000 m

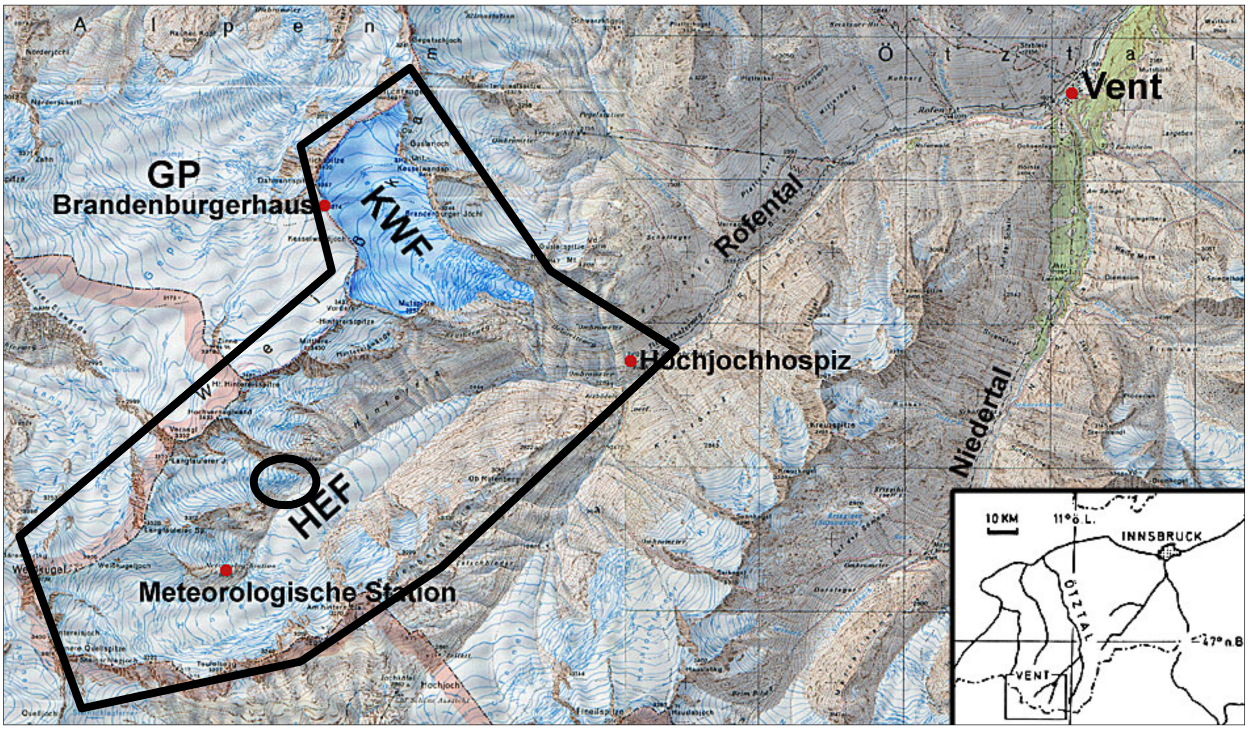

Figure 2: Hintereisferner study site with the area covered by the DEM derived from laser scanner data (36 km^2).

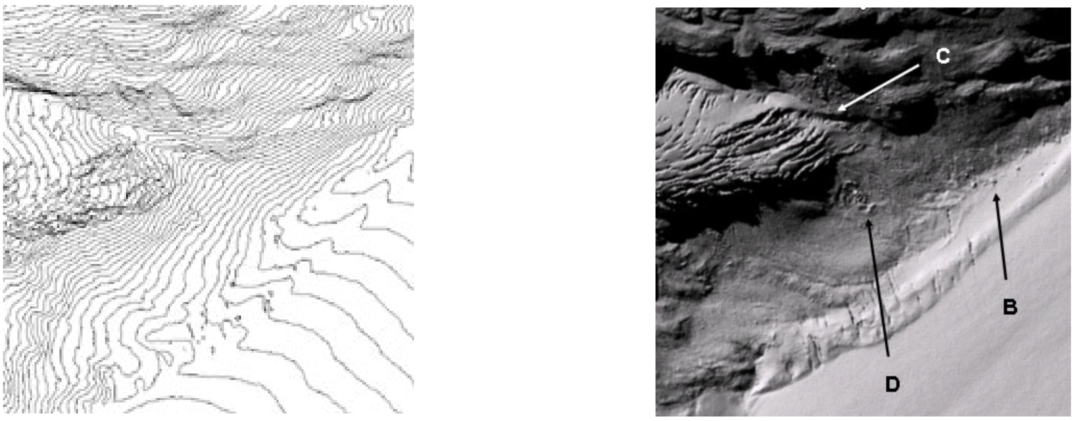

Figure 3: Confluence area of Langtaufererjochferner and Hintereisferner (marked with circle in Fig. 2).
a)5m contour lines b) 1m contour lines c) TIN with hillshade;
B = boulders C = crevasses D = ice boulders

The 14 flight paths follow the SW-NE direction of the longitudinal axis of Hintereisferner. As an overall outcome ca 27.5 million points with X-, Y- and Z-coordinates were recorded, thus resulting in an average density of over 750.000 points per km², with an average distance between the points of less than 1.15 m. Additionally, for each data point a value of the intensity of the reflected laser pulse has been stored. The characteristics of the data are listed in *table 2*.

Table 2: Characteristics of the data acquisition flight of 10 Oct 2001

Area	ca 36 km^2
Number of flight paths	14
Swath width	ca 500 m
Average altitude above ground	ca 1000 m
Number of data points (X, Y, Z; I)	27.625.916
Density of data points	769.524 points/km²
Average distance between data points	1.14 m

Data Processing

After the acquisition the raw data were pre-processed by TopScan GmbH. The pre-processing process comprises the determination of the absolute position of the laser scan system during the flight by analysis of the time-synchronized GPS and INS data, calculation of the relative coordinates, the system calibration and finally the calculation und delivery of the coordinates in WGS 84. For the differential correction of the sensor position GPS data from a nearby permanent receiving station (Krahberg) could be used. For the calibration of the system a calibration area in Obergurgl was used. A detailed overview on the pre-processing steps is given by Wever (1999).

After pre-processing a Triangulated Irregular Network (TIN) was calculated using all available data points. From this TIN contour lines were derived. For first visual interpretation, a shaded image of the TIN was derived. As an example *Figure 3* shows a shaded image of a part of Hintereisferner as well as contour line maps with different intervals.

FIRST RESULTS, CONCLUSIONS AND EXPECTATIONS

Due to the very recent acquisition of the first data the processing and analysis is still in its initial stages and therefore the results are only preliminary.

Compared to the traditional techniques of the geodetic method, used for both the modelling of the glacier surface and the quantification of changes in volume, in this example the surface of the glacier is represented by far more data points. Thus, the interpolation distance has become very small and the surface of the glacier is far better represented than by any other technique yet applied. The DEM derived from this data set describes the surface structure of the glacier in more detail than has been achieved so far, due to former technical or financial limitations. Even small geomorphological details are represented as shown by the visualisation. *Figure 3(c)* shows some examples, like crevasses of different sizes, boulders on moraine ridges and remnants of dead-ice of an ice-fall event that took place in July 2001.

The visualisation of the first results of airborne data acquisition at Hintereisferner shows the potential of this technique for glaciological applications, e.g. for mass-balance measurements using the geodetic method which requires high accuracy. Therefore the first step in the data analysis has to be to check for accuracy. This can be done by comparing laser scan points with known geodetic points. During further flights within the project the synchronous acquisition of aerial photographs is planned and, in consequence, the comparison with a DEM derived by traditional photogrammetric methods will be possible. In addition, the utilisation of terrestrial photogrammetry will provide precise reference data. The DEMs can be integrated into a Geographic Information System that offers additional opportunities for the analysis of the data points.

The time span of the flights covers one glaciological mass balance year (2001-2002). The multitemporal analysis and evaluation of the derived Digital Elevation Models (DEMs) provides a means to detect changes at the glacier surface in terms of elevation. Therefore it can be used for calculating the changes of glacier ice volume in time ($\Delta V/\Delta t$). A comparison will be possible with mass balance data derived by the direct glaciological method and geodetic method based on terrestrial measurements. Both methods are applied regularly at Hintereisferner. Furthermore, a certain focus can be laid on the observation of the accumulation and ablation of the snow cover. Since airborne laser scanning is a fairly young technology and there have been only a few applications on ice and snow surfaces until now, there is a demand and a potential for further research activities. Therefore the work presented here is only preliminary but is very promising.

ACKNOWLEDGEMENTS

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